



Overview and Recent Accomplishments of Advanced Mirror Technology Development (AMTD) for Very Large Space Telescopes

H. Philip Stahl, MSFC

AMTD is a funded NASA Strategic Astrophysics Technology (SAT) project

SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013



Top Level

Most future space telescope missions require mirror technology.

Just as JWST's architecture was driven by launch vehicle, future mission's architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures.

To provide science community with options, we must pursue multiple technology paths.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

- Very Smooth Surfaces < 10 nm rms
- Thermal Stability Low CTE Material
- Mechanical Stability High Stiffness Mirror Substrates



AMTD Objective

Our objective is to mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

This technology must enable missions capable of both general astrophysics & ultra-high contrast observations of exoplanets.

To accomplish our objective,

- We use a science-driven systems engineering approach.
- We mature technologies required to enable the highest priority science AND result in a high-performance low-cost low-risk system.



AMTD Team

AMTD uses a science-driven systems engineering approach which depends upon collaboration between a Science Advisory Team and a Systems Engineering Team.

We have assembled an outstanding team from academia, industry, and government with extensive expertise in

- UVOIR astrophysics and exoplanet characterization,
- monolithic and segmented space telescopes, and
- optical manufacturing and testing.



AMTD Project Technical Team

Principle Investigator		Systems Engineering	
Dr. H. Philip Stahl	MSFC	Dr W. Scott Smith	MSFC
Science Advisory		Engineering	
Dr. Marc Postman	STScI	Laura Abplanalp	Exelis
Dr. Remi Soummer	STScI	Ron Eng	MSFC
Dr. Arund Sivaramakrishnan	STScI	William Arnold	MSFC
Dr. Bruce A. Macintosh	LLNL		
Dr. Olivier Guyon	UoAz		
Dr. John E. Krist	JPL		
Integrated Modeling		AMTD-2 Proposal	
Gary Mosier	GSFC	Tony Hull	Schott
William Arnold	MSFC	Andrew Clarkson	L3-Brashear
Anis Husain	Ziva		
Jessica Gersh-Range	Cornel		

Funding

NASA ROSES SAT (10-SAT10-0048)

Space Act Agreement (SAA8-1314052) with Ziva Corp

NASA Graduate Student Research Program (NNX09AJ18H)



Heritage

AMTD builds on over 30 yrs of US Gov mirror technology development:

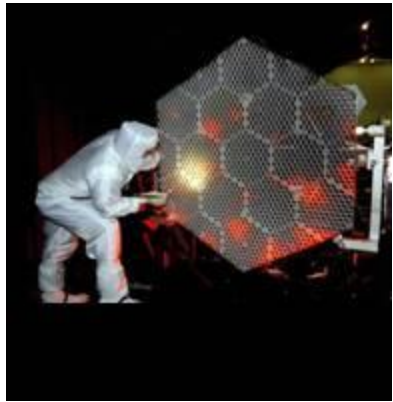
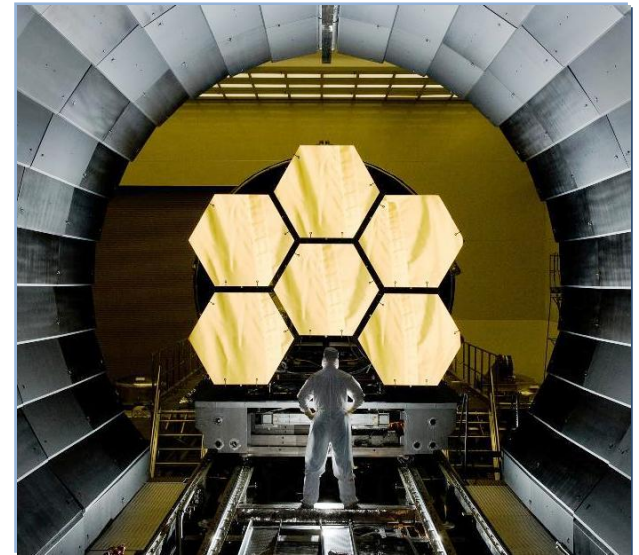
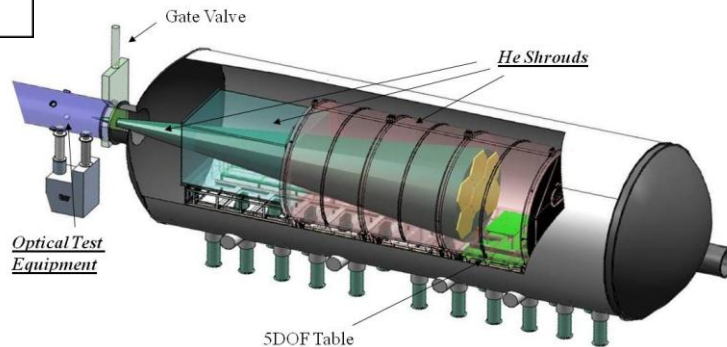
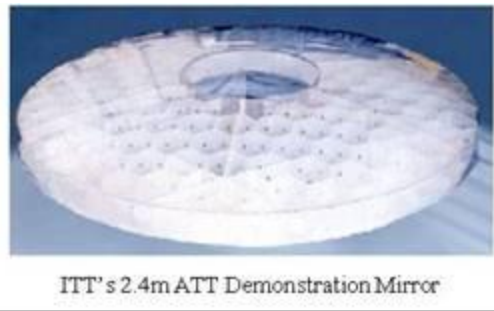


Figure 3-7: LAMP (left), AOSD (center) and SMT (right)





AMTD Team

Science & Engineering work collaboratively to insure that we mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

- derive engineering specifications for monolithic & segmented mirrors which provide on-orbit science performance needs AND satisfy implementation constraints
- identify technical challenges in meeting these specifications,
- iterate between science needs and engineering specifications to mitigate the challenges, and
- prioritize technology development which yields greatest on-orbit performance for lowest cost and risk.

STOP (structural, thermal, optical performance) models are used to help predict on-orbit performance & assist in trade studies.



Tasks

Derive engineering specifications for a future monolithic or segmented space telescope based on science needs & implementation constraints.

Mature 6 inter-linked critical technologies.

- *Large-Aperture, Low Areal Density, High Stiffness Mirrors*
- *Support System*
- *Mid/High Spatial Frequency Figure Error*
- *Segment Edges*
- *Segment-to-Segment Gap Phasing*
- *Integrated Model Validation*



Philosophy

Simultaneous technology maturation because all are required to make a primary mirror assembly (PMA); AND, it is the PMA's on-orbit performance which determines science return.

- PMA stiffness depends on substrate and support stiffness.
- Ability to cost-effectively eliminate mid/high spatial figure errors and polishing edges depends on substrate stiffness.
- On-orbit thermal and mechanical performance depends on substrate stiffness, the coefficient of thermal expansion (CTE) and thermal mass.
- Segment-to-segment phasing depends on substrate & structure stiffness.

We are deliberately pursuing multiple design paths to enable either a future monolithic or segmented space telescope

- Gives science community options
- Future mission architectures depend on future launch vehicles, AND
- We cannot predict future launch vehicle capacities



Goals, Progress & Accomplishments

Key

Done

Stopped

In-Process

Not Started Yet

Systems Engineering:

- **derive from science requirements monolithic mirror specifications**
- **derive from science requirements segmented mirror specifications**

Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:

- **make a subsection mirror via a process traceable to 500 mm deep mirrors**

Support System:

- **produce pre-Phase-A point designs for candidate primary mirror architectures;**
- **demonstrate specific actuation and vibration isolation mechanisms**

Mid/High Spatial Frequency Figure Error:

- 'null' polish a 1.5-m AMSD mirror & subscale deep core mirror to a < 6 nm rms zero-g figure at the 2°C operational temperature.

Segment Edges:

- **demonstrate an achromatic edge apodization mask**

Segment to Segment Gap Phasing:

- **develop models for segmented primary mirror performance; and**
- **test prototype passive & active mechanisms to control gaps to ~ 1 nm rms.**

Integrated Model Validation:

- **validate thermal model by testing** the AMSD and **deep core mirrors at 2°C**; and
- **validate mechanical models by static load test.**



9 Publications from Year 1

- Stahl, H. Philip, *Overview and Recent Accomplishments of the Advanced Mirror Technology Development (AMTD) for large aperture UVOIR space telescopes project*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013.
- Stahl, H. Philip, W. Scott Smith, Marc Postman, *Engineering specifications for a 4 meter class UVOIR space telescope derived from science requirements*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013.
- Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.
- Matthews, Gary, et al, *Processing of a stacked core mirror for UV applications*, SPIE Conference on Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, 2013.
- Eng, Ron, et. al., *Cryogenic optical performance of a lightweighted mirror assembly for future space astronomical telescopes: correlation of optical test results and thermal optical model*, SPIE Conference on Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, 2013.
- Sivaramakrishnan, Anand, Alexandra Greenbaum, G. Lawrence Carr, and Randy J. Smith, *Calibrating apodizer fabrication techniques for high contrast coronagraphs on segmented and monolithic space telescopes*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013.
- Arnold, William et al, *Next generation lightweight mirror modeling software*, SPIE Conference on Optomechanical Engineering, 2013.
- Arnold, William et al, *Integration of Mirror design with Suspension System using NASA's new mirror modeling software*, SPIE Conference on Optomechanical Engineering, 2013.
- Gersh-Range, Jessica A., William R. Arnold, Mason A. Peck, and H. Philip Stahl, *A parametric finite-element model for evaluating segmented mirrors with discrete edgewise connectivity*, SPIE Proceedings 8125, 2011, DOI:10.1117/12.893469



Engineering Specifications

To be discussed by Phil Stahl



Telescope Performance Requirements

Telescope Specifications depend upon the Science Instrument.

Telescope Specifications have been defined for 3 cases:

- 4 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an External Occulter

WFE Specification is before correction by a Deformable Mirror

WFE/EE Stability and MSF WFE are the stressing specifications

Specifications have not been defined for a Visible Nulling Coronagraph or phase type coronagraph.



Large-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates

To be discussed by Gary Matthews



Large Substrates: Technical Challenge

Future large-aperture space telescopes (regardless of monolithic or segmented) need ultra-stable mechanical and thermal performance for high-contrast imaging.

This requires larger, thicker, and stiffer substrates.

Current launch vehicle capacity also requires low areal density.



Large Substrate: Achievements

Successfully demonstrated a new fabrication process (stacked core low-temperature fusion).

New process offers significant cost and risk reduction over incumbent process. It is difficult (and expensive) to cut a deep-core substrate to exacting rib thickness requirements. Current SOA is ~300 mm on an expensive custom machine. But, < 130 mm deep cores can be done on commercial machines.

Extended state of the art for deep core mirrors from less than 300 mm to greater than 400 mm.

Successfully 're-slumped' a ULE fused substrate.

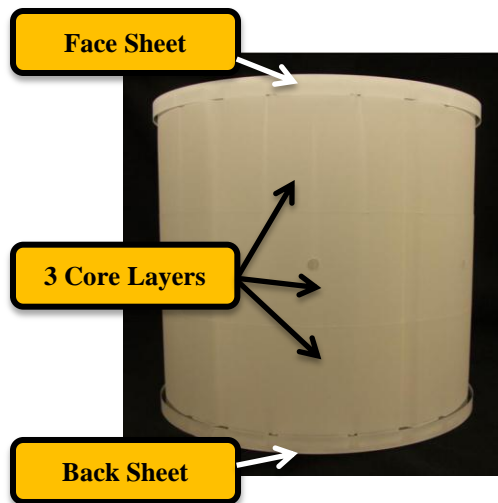
This is interesting because it allows generic substrates to be assembled and place in inventory for re-slumping to a final radius of curvature.



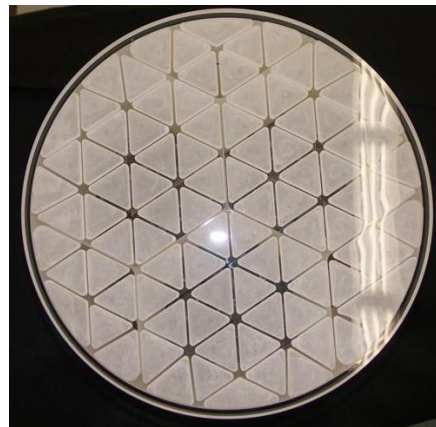
43 cm Deep Core Mirror

Exelis successfully demonstrated 5-layer 'stack & fuse' technique which fuses 3 core structural element layers to front & back faceplates.

Made 43 cm 'cut-out' of a 4 m dia, > 0.4 m deep, 60 kg/m^2 mirror substrate.



Post-Fusion Side View
3 Core Layers and Vent Hole Visible



Post-Fusion Top View
Pocket Milled Faceplate



Post Slump:
2.5 meter Radius of Curvature

This technology advance leads to stiffer 2 to 4 to 8 meter class substrates at lower cost and risk for monolithic or segmented mirrors.

Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.



Mid/High Spatial Frequency Figure Error

To be discussed by Gary Matthews



Mid/High Spatial Frequency Figure Error

Technical Challenge:

- High-contrast imaging requires a very smooth mirror (< 10 nm rms)
- Mid/High spatial errors (zonal & quilting) can introduce artifacts
- DMs correct low-spatial errors, not mid/high spatial errors
- On-orbit thermal environment can stress mirror introducing error

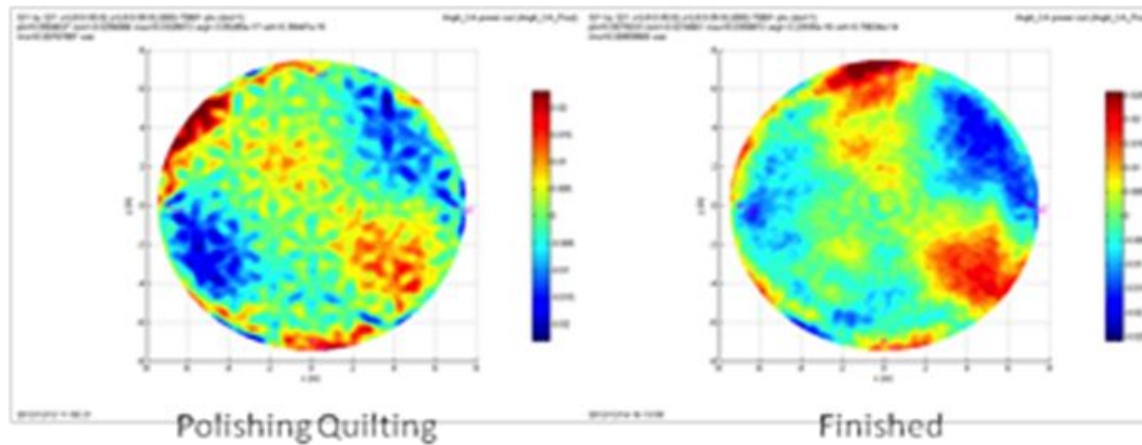
Achievements:

- AMTD partner Exelis designed facesheet to minimize mid/high spatial frequency quilting error from polishing pressure and thermal stress.
- Exelis ion polishing process produced 5.4 nm rms surface
- Thermal test showed no measurable cryo-deformation or quilting

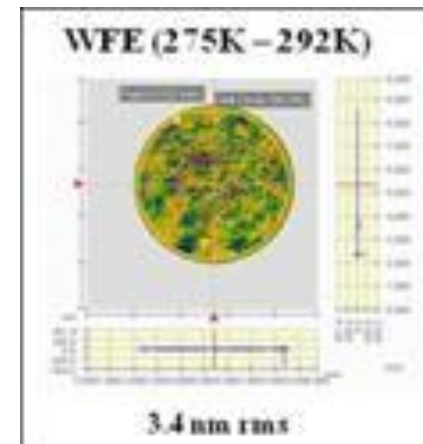
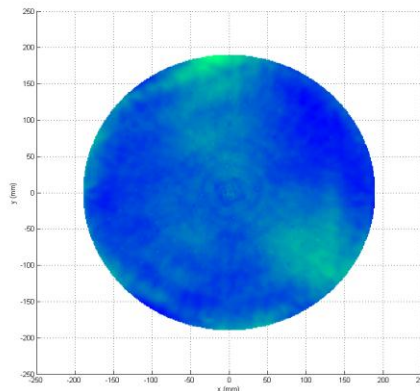


Mid/High Spatial Frequency Error

Exelis polished 43 cm deep-core mirror to a zero-gravity figure of 5.5 nm rms using ion-beam figuring to eliminate quilting.



MSFC tested 43 cm mirror from 250 to 300K. Its thermal deformation was insignificant (smaller than 4 nm rms ability to measure the shape change)





Integrated Model Validation

To be discussed by Ron Eng



Integrated Model Validation

Technical Challenge:

- On-orbit performance is determined by mechanical & thermal stability
- As future systems become larger, compliance cannot be 100% tested
- Verification will rely on sub-scale tests & validated high fidelity models

Achievement:

- Developed new opto-mechanical tool to create high-fidelity models
- Created models to predict gravity sag & 2C thermal gradients
- Validated models by interferometric and thermal imaging test



Deep Core Thermal Model

Thermal Model of 43 cm deep core mirror generated and validate by test.

43 cm deep core mirror tested from 250 to 300K

Test Instrumentation

4D Instantaneous Interferometer to measure surface Wavefront Error

InSb Micro-bolometer to measure front surface temperature gradient to 0.05C

12 Thermal Diodes.



Figure 8: 43-cm mirror test setup.

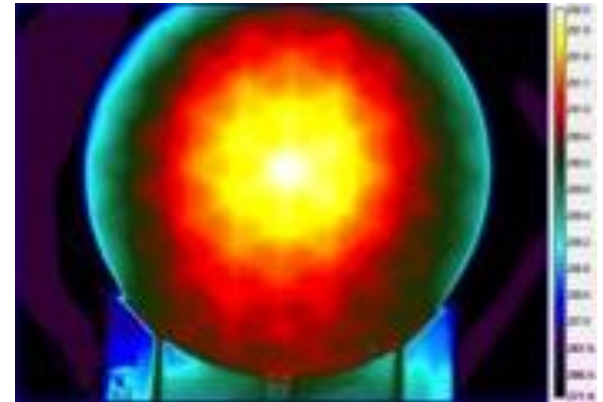
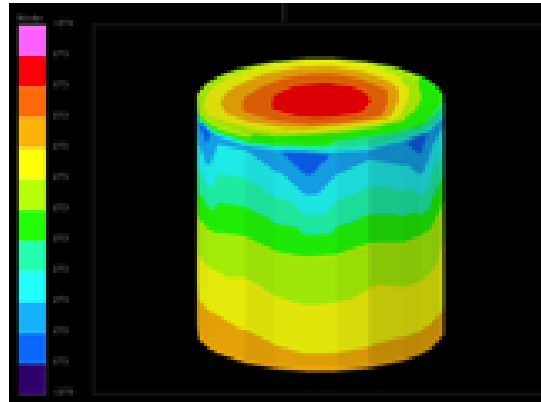


Figure 9: Predicted Thermal Model (left) vs. Measure Performance (right)

NOTE: This was first ever XRCF test using thermal imaging to monitor temperature



Segment Edges



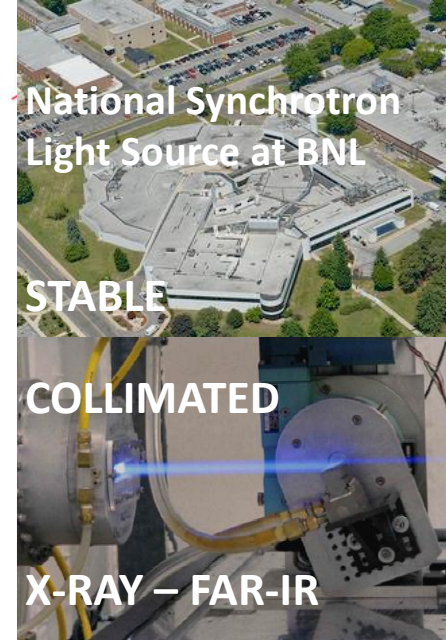
Segment Edges

Technical Challenge:

- Segmented primary mirror edge quality impacts PSF for high-contrast imaging applications and contributes to stray light noise.
- Diffraction from secondary mirror obscuration and support structure also impacts performance.

Achievement

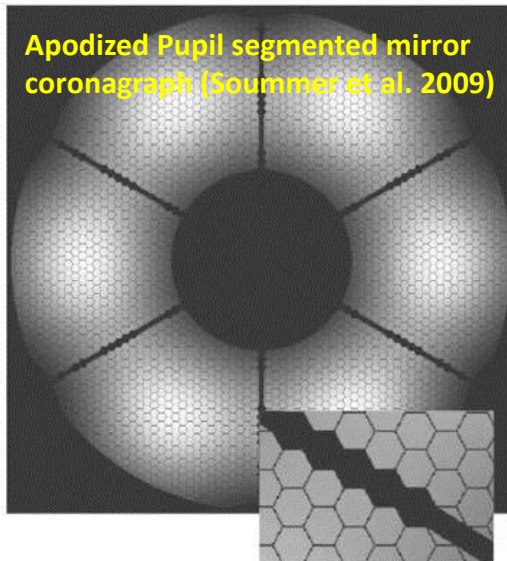
- AMTD partner STScI successfully demonstrated an achromatic edge apodization process to minimize segment edge diffraction and straylight on high-contrast imaging PSF.



Primary mirror segment gap apodization in the optical

A. Sivaramakrishnan, G. L. Carr, R. Smith, X. X. Xi, & N. T. Zimmerman

Apodized Pupil segmented mirror
coronagraph (Soummer et al. 2009)



Apodization mitigates segment gaps

Achromatic apodization in collimated space

Tolerancing can be tight

Gemini Planet Imager (1.1-2.4 μm) – 0.5% accuracy req.

UVOIR space coronagraphy - 0.55 – 1.1 μm

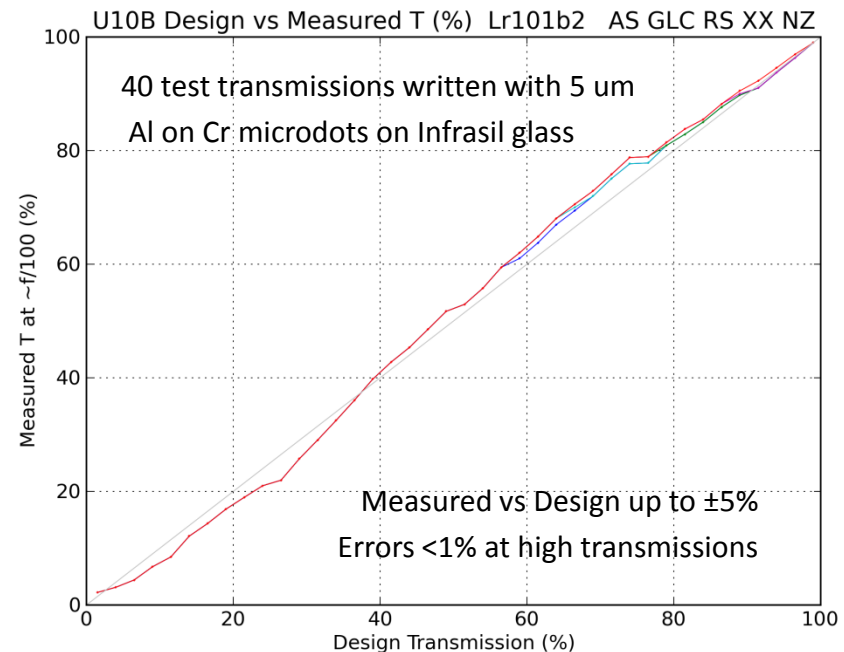
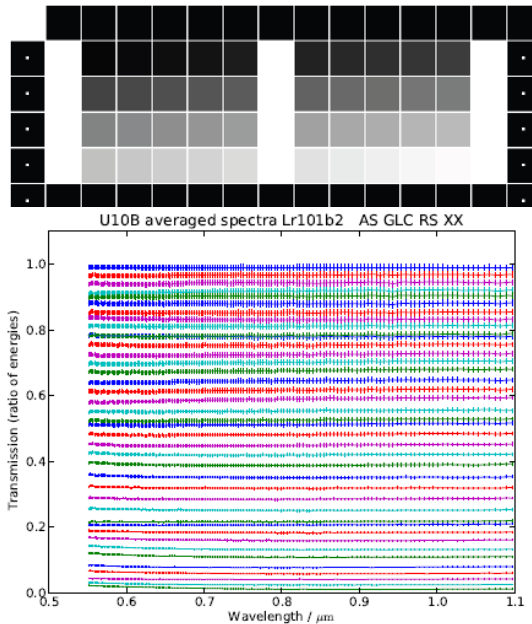
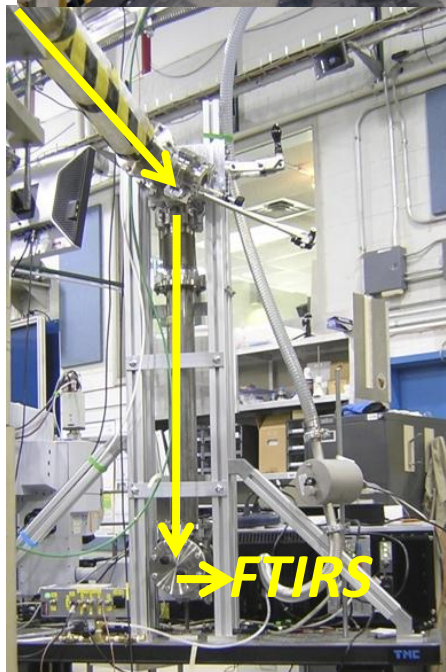
Metal-on-glass dots look OK

Next

Develop & confirm on reflective surfaces

Reqs. on accuracy, reflectivity, absorption/, polarization?

Use larger dots to reduce non-linearity



Use of the National Synchrotron Light Source, Brookhaven National Laboratory, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886.



Support System

To be discussed by Bill Arnold



Support System

Technical Challenge:

- Large-aperture mirrors require large support systems to survive launch & deploy on orbit in a stress-free and undistorted shape.

Accomplishments:

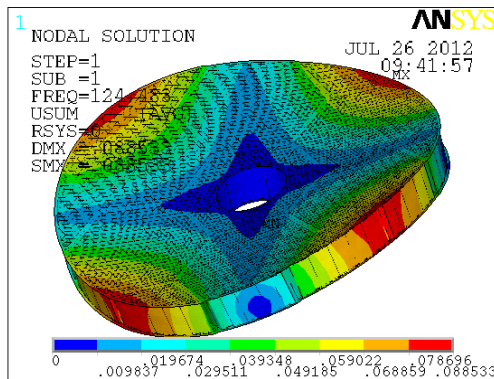
- Developed a new modeler tool for ANSYS which can produce 400,000-element models in minutes.
- Tool facilitates transfer of high-resolution mesh to mechanical & thermal analysis tools.
- Used our new tool to compare pre-Phase-A point designs for 4-meter and 8-meter monolithic primary mirror substrates and supports.



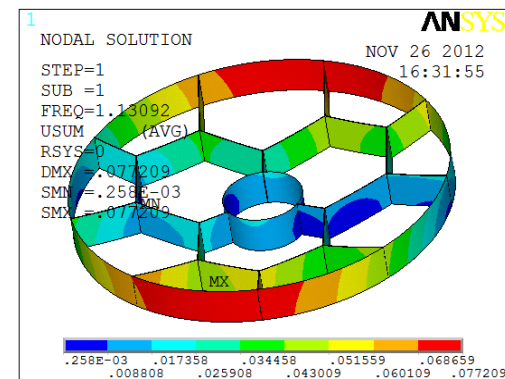
Design Tools and Point Designs

AMTD has developed a powerful tool which quickly creates monolithic or segmented mirror designs; and analyzes their static & dynamic mechanical and thermal performance.

Point Designs: AMTD has used these tools to generate Pre-Phase-A point designs for 4 & 8-m mirror substrates.



Free-Free 1st Mode: 4 m dia 40 cm thick substrate



Internal Stress: 4 m dia with 6 support pads

Support System: AMTD has used these tools to generate Pre-Phase-A point designs for 4-m mirror substrate with a launch support system.



Monolithic Substrate Point Designs

4-m designs are mass constrained to 720 kg for launch on EELV

8-m designs are mass constrained to 22 mt for launch on SLS



Trade Study Concept #1: 4 m Solid

Design:

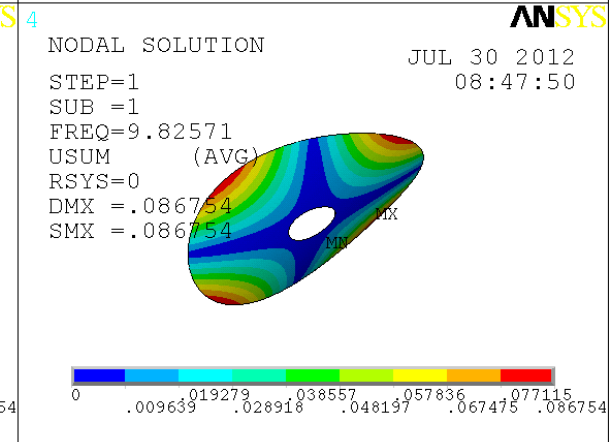
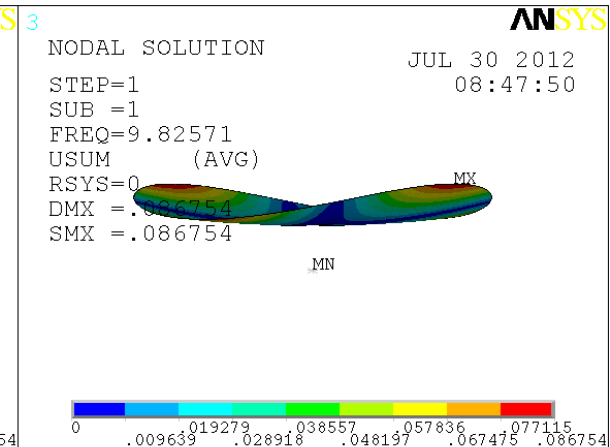
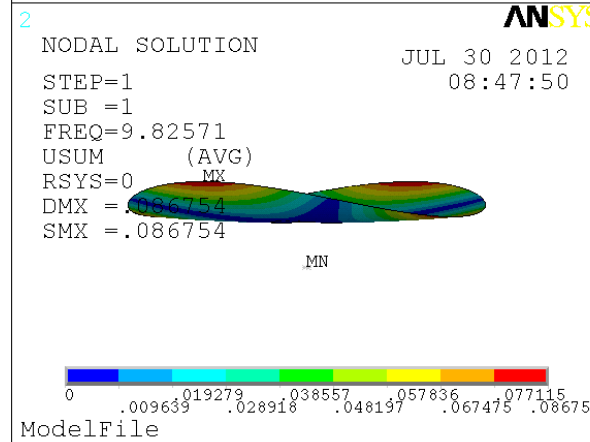
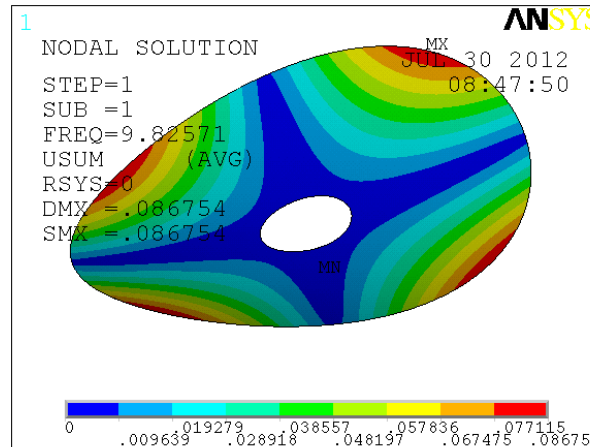
Diameter 4 meters

Thickness 26.5 mm

Mass 716 kg

First Mode 9.8 Hz

SET	TIME/FREQ
1	9.8257
2	9.8257
3	23.548
4	23.552
5	41.021
6	41.021
7	62.123
8	62.123
9	86.807
10	86.807

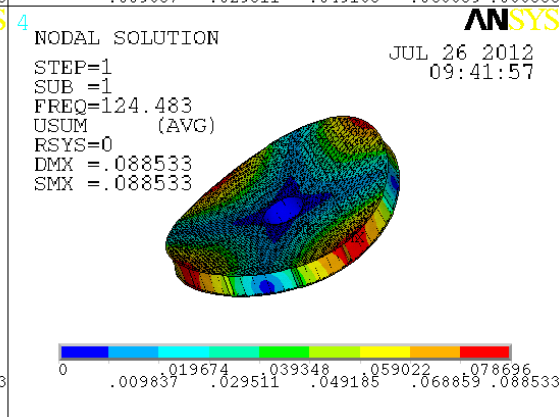
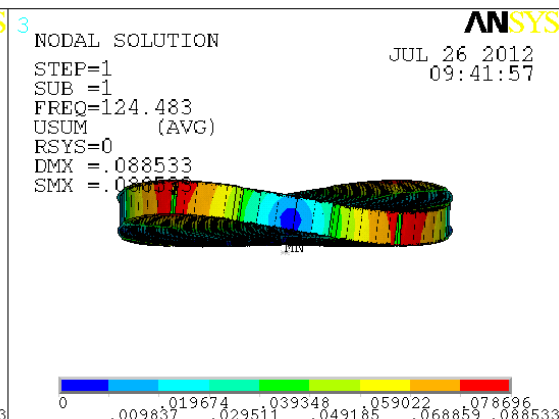
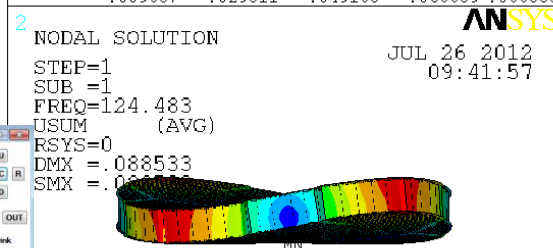
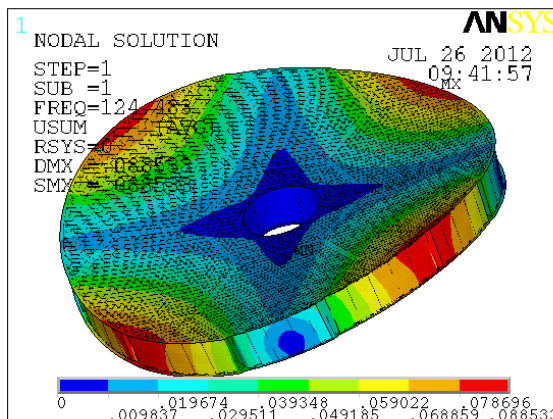
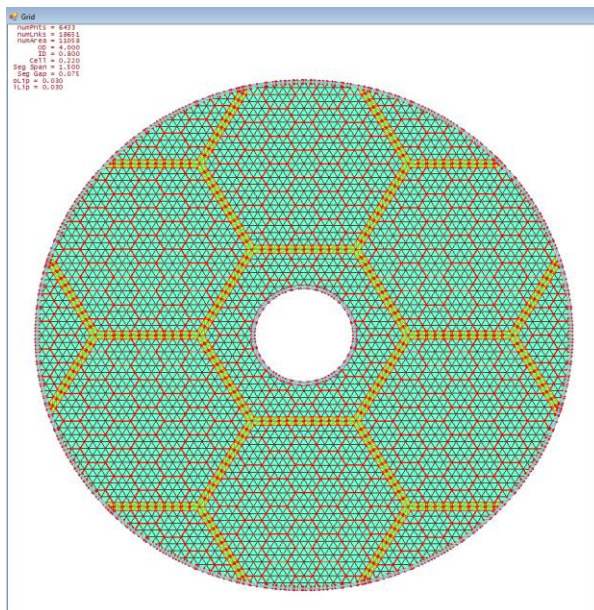




Trade Study Concept #2: 4 meter Lightweight

Design:

Diameter 4 meters
Thickness 410 mm
Facesheet 3 mm
Mass 621 kg
First Mode 124.5 Hz



SET	TIME/FREQ
1	124.48
2	124.77
3	199.39
4	257.85
5	275.88
6	321.22
7	321.60
8	350.07
9	350.08
10	350.33



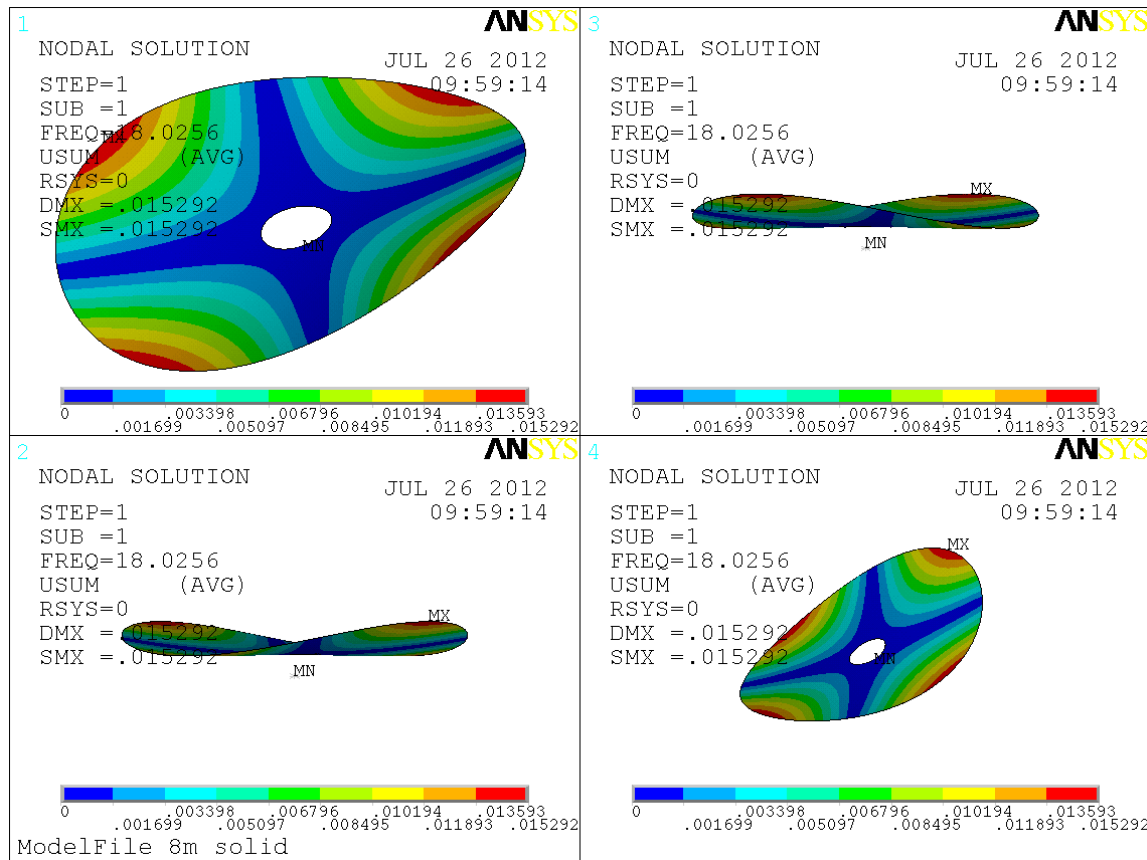
Trade Study Concept #3: 8 meter Solid 22 MT

Design:

Diameter 8 meter
Thickness 200 mm
Mass 21,800 kg
First Mode 18 Hz

Same as ATLAST Study

SET	TIME/FREQ
1	18.026
2	18.035
3	42.449
4	42.452
5	47.827
6	74.041
7	74.045
8	75.174
9	75.176
10	112.96





Trade Study Concept #4: 8 meter Lightweight

Design:

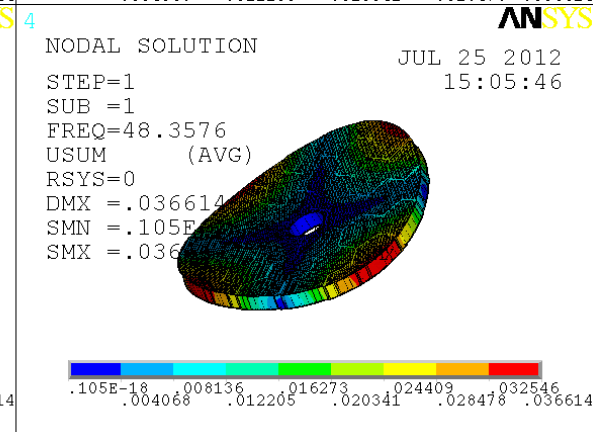
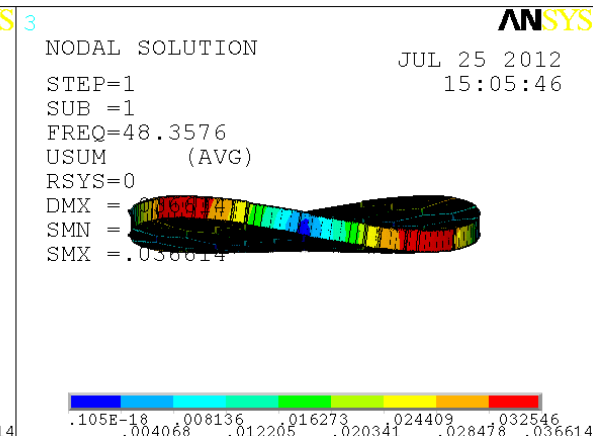
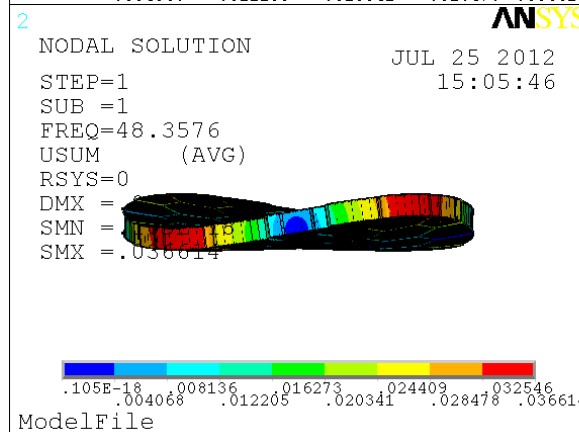
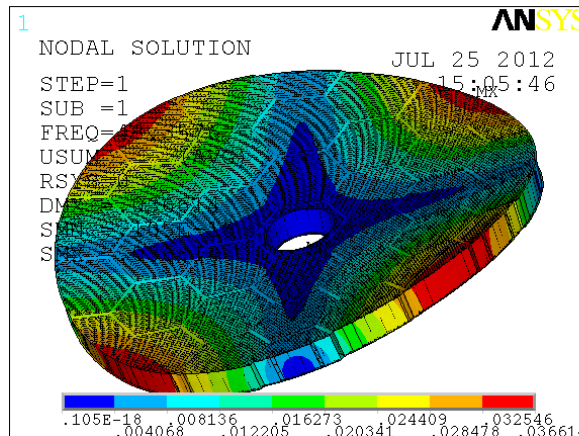
Diameter 8 meter

Thickness 510 mm

Facesheet 7 mm

Mass 3,640 kg

First Mode 48.4 Hz





Modeling Tool

To be discussed by Bill Arnold



Program Control Window

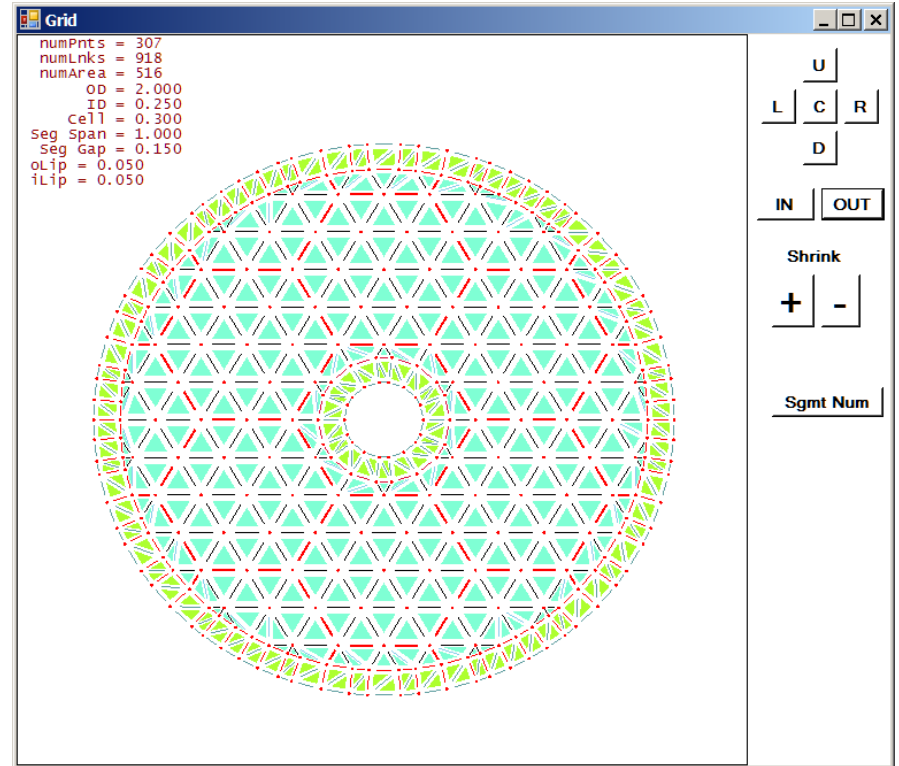
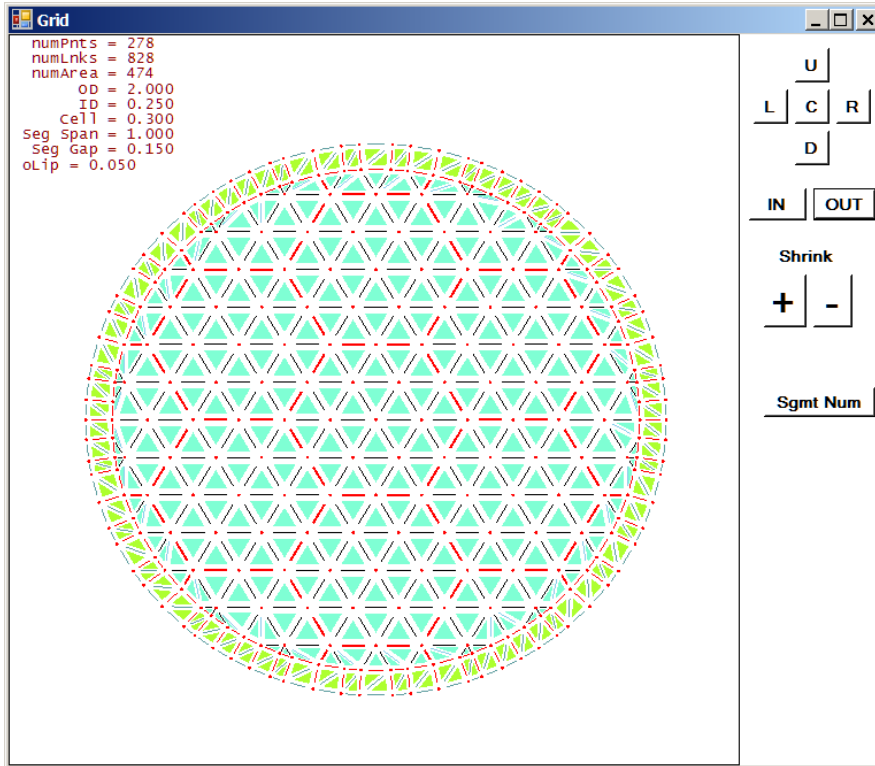
Arnold Lightweight Mirror Modeler (Ver 2.0) [X]

Outer Dia	<input type="text" value="2"/>	Supports <input type="radio"/> Each Segment <input checked="" type="radio"/> Whole Mirror	DISPLAY GRID				
Inner Dia	<input type="text" value="0.25"/>			DISPLAY MODEL			
Cell Width	<input type="text" value="0.3"/>				WRITE MODEL		
Lip Inner	<input type="text" value="0.05"/>					SAVE RESTORE	
Segment Lip	<input type="text" value="0.05"/>						MERGE NODES
Mirror Lip	<input type="text" value="0.1"/>						
Num Rings	<input type="text" value="0"/>	<input checked="" type="checkbox"/> Show Whole Grid					
Sgmt Span	<input type="text" value="1"/>	<input type="checkbox"/> Show Supports					
Sgmt Gap	<input type="text" value="0.15"/>	<input type="checkbox"/> Show Fillets					
Merge Tol	<input type="text" value="0.025"/>	Modal (PSD) Boule Mapping					
Grid Zoom	<input type="text" value="1"/>	Grid Options Optical Reals Core Hexapod Axial Radial Inertial Loads					
Segment Shown	<input type="text" value="1"/>	<input type="checkbox"/> Outer Sgmt Lip <input type="checkbox"/> Isogrid Front <input type="radio"/> Cell Level 0					
Srink Factor	<input type="text" value="0.05"/>	<input type="checkbox"/> Outer Mirror Lip <input type="checkbox"/> Isogrid Back <input type="radio"/> Cell Level 1					
		<input type="checkbox"/> Inner Mirror Lip <input type="checkbox"/> Backface Holes <input checked="" type="radio"/> Cell Level 2					
		<input type="checkbox"/> Circular Segment <input type="checkbox"/> Core Projection					
		<input type="checkbox"/> Circular Mirror <input type="checkbox"/> Include Fillets					
		<input checked="" type="checkbox"/> Seal Ring Outer <input type="checkbox"/> Off Center Pattern					
		<input checked="" type="checkbox"/> Seal Ring Inner <input type="checkbox"/> No Backsheet					
		<input checked="" type="checkbox"/> Seal Ring Mirror <input type="checkbox"/> Central Hole					
		<input type="checkbox"/> Segment Lip Ribs					

Status

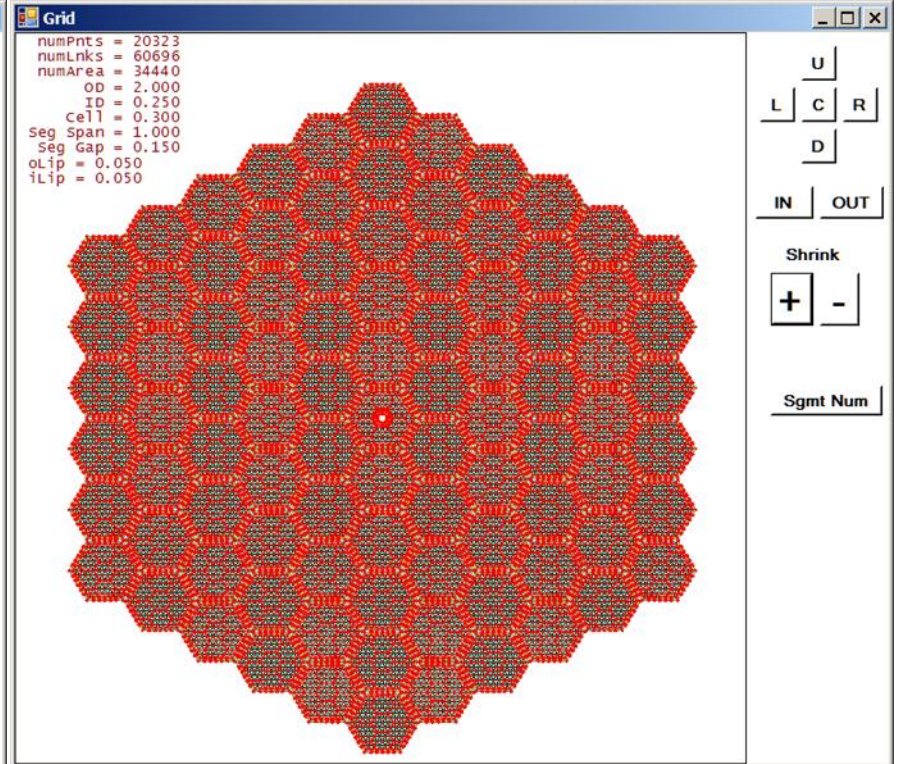
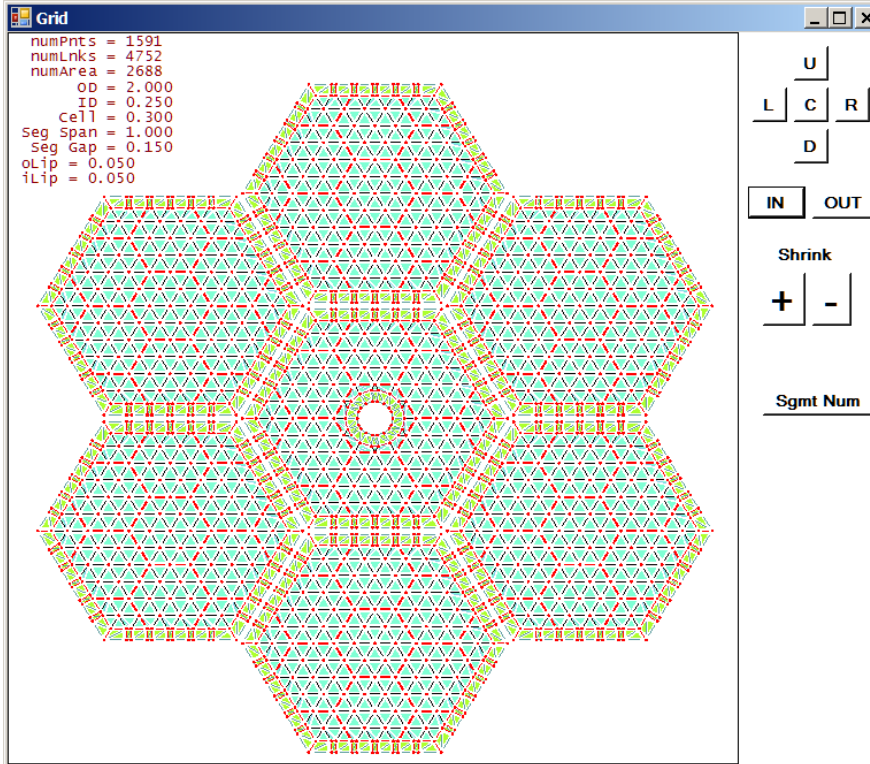


Monolithic Mirrors





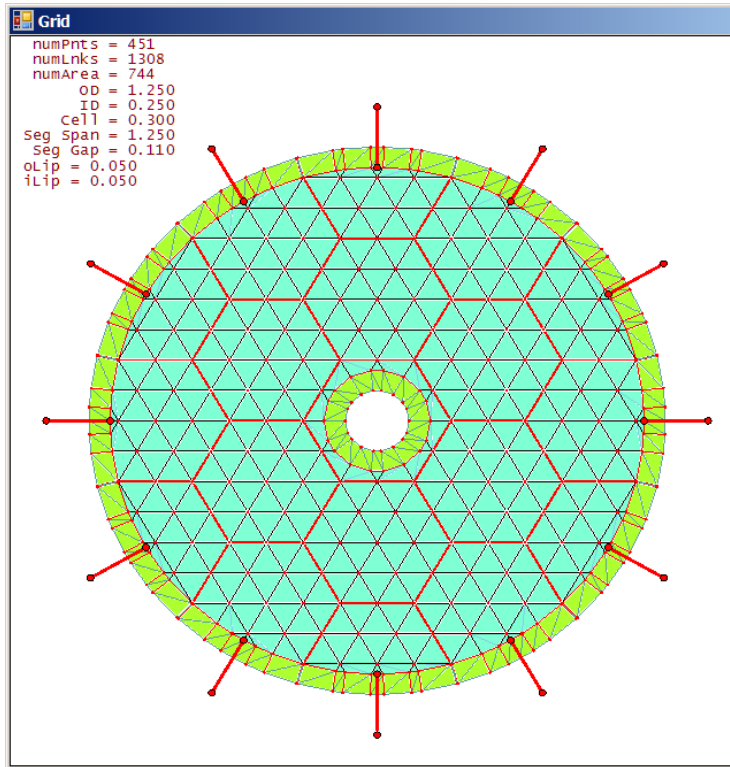
Segmented Mirrors





Support Systems

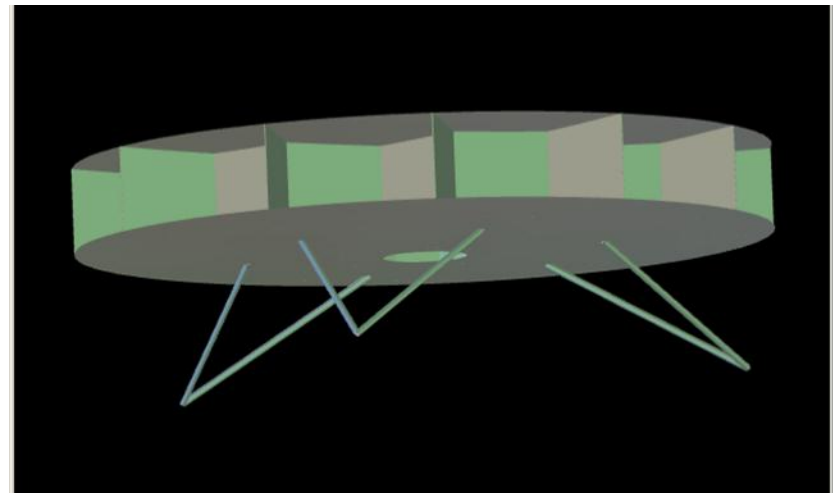
Radial



Axial



Hexapod





Segment to Segment Gap Phasing



Segment to Segment Gap Phasing

Technical Challenge:

- To avoid speckle noise which can interfere with exo-planet observation, Internal coronagraphs require segment to segment dynamic co-phasing error < 10 pm rms between WFSC updates.

Achievements:

- Built a Delron plastic pendulum to investigate utility of correlated magnetic interfaces.
- Correlated magnetic interface provided only marginally improved dampening over conventional magnets.
- Given the inability to reduce dynamic below the required level, we plan no further investigation of this approach.

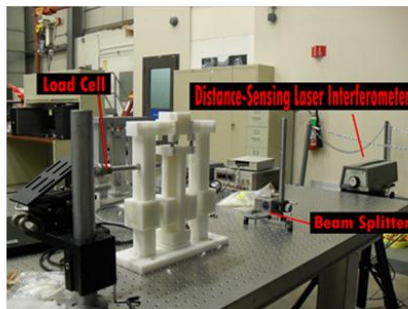


Figure 6: Delron Pendulum Test Setup

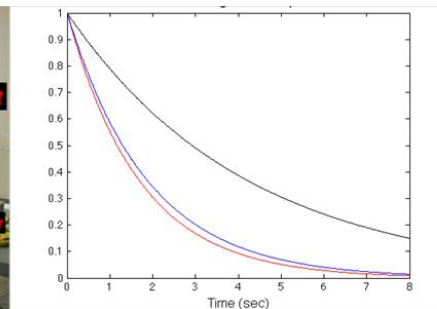
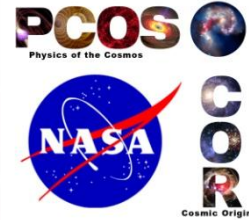


Figure 7: Oscillation Amplitude vs. Time for Unconstrained (black), Conventional Magnetic Interface (blue), and Correlated Magnetic Interface (red)

Advanced Mirror Technology Development

PI: Phil Stahl/MSFC



Description and Objectives:

- Mature the TRL of fine positioning mechanism technology challenges for primary mirrors of future large-aperture Cosmic Origin UVOIR space telescopes
- Targeted specifically for segmented optics design path
- Conduct prototype development and testing
- Trace metrics to science mission error budget

Key Challenge/Innovation:

- Operation of low voltage piezo based fine actuator
- Thermal compensation in complete strut
- Develop low noise actuator drive electronics

Approach:

- Fabricate fine actuator of AMSD active strut
- Design and fabricate test bed
- Performance test fine actuator at design load

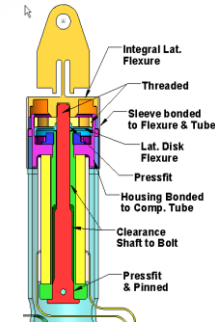
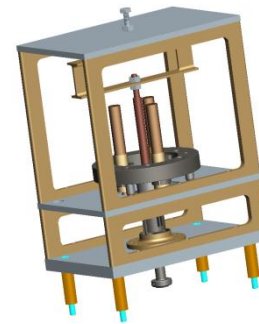
Key Collaborators:

- Dr. Scott Smith, Ron Eng and Mike Effinger/ NASA MSFC
- Bill Arnold/Defense Acquisition Inc., Gary Mosier/GSFC
- Laura Abplanalp, Scott Kraus, Mike OBrien/Exelis

Development Period:

- Nov 2012 –Feb 2014

Actuator
Test Bed



Active Strut Fine Motion
Actuator

Accomplishments and Next Milestones:

- Actuator drawings complete and quoted
- Test set drawing complete and quoted
- Drive electronics and Data Acquisition System designs initiated
- Vendor selection for fabricated parts under way
- Complete electronics design and initial layout for fabrication

Application:

- Flagship optical missions
- Explorer type optical missions
- Department of Defense and commercial observations

TRLin = TRL2 (conceptual design only)

TRLcurrent = TRL3 (proof of concept, lab tested)

TRLtarget = half step increase



Conclusions

AMTD uses a science-driven systems engineering approach to define & execute a long-term strategy to mature technologies necessary to enable future large aperture space telescopes.

Because we cannot predict the future, we are pursuing multiple technology paths including monolithic & segmented mirrors.

Assembled outstanding team from academia, industry & government; experts in science & space telescope engineering.

Derived engineering specifications from science measurement needs & implementation constraints.

Maturing 6 critical technologies required to enable 4 to 8 meter UVOIR space telescope mirror assemblies for both general astrophysics & ultra-high contrast exoplanet imaging.

AMTD achieving all its goals & accomplishing all its milestones